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Development of Superconducting Wind Turbine Generators

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Invited Paper

Abstract

In this paper the commercial activities in the field of superconducting machines, particularly superconducting wind turbine generators, are reviewed and presented. Superconducting generators have the potential to provide a compact and light weight drive train at high torques and slow rotational speeds, because high magnetic fields can be produced by coils with very little loss.

Three different superconducting wind turbine generator topologies have been proposed by three different companies. One is based on low temperature superconductors (LTS); one is based on high temperature superconductors (HTS); and one is a fully superconducting generator based on MgB_2. It is concluded that there is large commercial interest in superconducting machines, with an increasing patenting activity.

Such generators are however not without their challenges. The superconductors have to be cooled down to somewhere between 4K and 50K, depending on what type of superconductor is employed, which poses a significant challenge both from a construction and operation point of view. The high temperature superconductors can facilitate a higher operation temperature and simplified cooling, but the current price and production volumes prohibit a large scale impact on the wind sector. The low temperature superconductors are readily available, but will need more sophisticated cooling.

Eventually the CoE from superconducting wind turbines, with particular emphasis on reliability, will determine if they become feasible or not and for such investigations large-scale demonstrations will be needed.

Keywords: direct drive wind turbines, superconducting machines, superconducting wind turbines, wind turbines

1 Introduction

The commercial wind industry has been firmly established with numerous companies specializing in the field of wind turbine manufacturing as well as development and operation of wind farms. The success of the wind industry is driven by its green credentials and the relatively low cost of energy (CoE). The CoE onshore has been as low as €52/MWh [1] and has thus given an excellent business case for the operator of the wind farms.

However, it has become more difficult to obtain planning permission onshore and particularly near the shoreline, where the wind conditions are favorable. This has driven the operators offshore, where planning permission is easier to obtain. As the wind conditions are more favorable offshore, the capacity factor is higher and hence each installed MW offshore gives more MWh per year, compared to the installed MW onshore. This naturally leads to higher annual energy delivery from offshore installations, but as the capital expenditure (CAPEX) and operational expenditure (OPEX) are significantly higher offshore the CoE is also higher (1).

$$CoE = \frac{Annualised\ CAPEX\ and\ OPEX}{Annual\ energy\ production} \tag{1}$$

To stay competitive with other forms of energy sources the focus, of wind turbine manufacturers, operators and research institutions over the last few years, has been on lowering the CoE from offshore wind farms.

This can be done by focusing on improving the reliability of the wind farms [2]; employing predictive condition monitoring systems (CMS) [3]; optimizing the wind farm layout [4]; improving the capacity factor [5]; and increasing the lifetime of the wind turbine [6]. One of the present trends is to reduce the CoE by increasing the size of the individual wind turbines, such that the installation and operation costs can be reduced [7]. The driver here is that the cost of offshore installations i.e.

foundation and electrical infrastructure, increases slowly with the size of the turbine. One could therefore reduce the CAPEX by installing larger offshore turbines. Additionally as there are fewer units to maintain, the OPEX can also be reduced, both of which result in a decreased CoE.

This only applies as long as the larger wind turbines can be acquired, installed and operated at a reasonable price. If the CoE does not reduce by increasing the size of the wind turbines further, the size hike would cease until a technology leap could allow the CoE to drop further by increasing the size again [7].

A trend over the last few years has been to employ rare earth permanent magnet generators, which allow for compact generators with high torque densities. Many of the manufacturers have removed the gearbox and chosen to use directly driven generators, which are expected to improve the reliability of the wind turbine and in this way reduce the CoE. Such direct drive permanent magnet generators are heavily dependent on rare earth magnets, the price of which has increased dramatically the last couple of years. The security of supply has also become an issue to bear in mind as developing the future wind turbine generators would require in approximately 6-800kg of rare earth permanent magnets for each MW of output power. This would in turn add to the pressure on other applications relying of rare earth materials and most likely be a cause for further price increase. To add to this, the demand for torque dense generators is increasing as the CoE is still driving the development of larger and larger wind turbines.

A generator technology that is nearly independent of rare earth materials and has notoriously high torque density is the superconducting generator. These generators have yet to be commercialized however several prototypes have demonstrated that construction of such machines is possible [8, 9, 10], and based on calculations it can be shown that torque densities of 2-3 times those of permanent magnet machines can be achieved.

In this paper the past and present development of superconducting machines is described. Some of the challenges associated with such machines are discussed and the requirements for the different superconducting materials are presented together with the current price. The commercial indicators showing the industrial interest in superconducting machines is described and the patent development in this area is discussed.

2 Superconductivity

This section gives an introduction to the basic properties of superconductivity when used in applications such as wind turbine generators [11].

2.1 History

Superconductivity was discovered in 1911 by Heike Kamerlingh Onnes, when he observed that the electrical resistance of mercury disappeared when it was cooled in liquid helium boiling at T = 4.2K (-269^{o}C). The vanishing of the resistance (R = 0Ω) inspired to naming this new class of material a superconductor and the transition temperature was called the critical temperature T_C.

In 1933 Meissner discovered that metallic superconductors are not just a perfect conductor, but they also expel the magnetic flux from an applied field by creating surface screening currents, which do not decay in time. This state with B = 0T inside a superconductor is denoted the Meissner state, but it can only exist as long as the applied flux density is lower than the critical flux density B_C. The metal Nb has the highest critical temperature (T_C = 9.2K) of the elements and a critical flux density of B_C ~ 0.2T. Nb is therefore useful in making superconducting electronics and wires, but one cannot use it to make high field superconducting electromagnets, since the magnetic field will suppress the superconducting state and turn the wire into a normal metal with finite resistance.

Extensive investigations in the 1950's and 1960's of metal alloys revealed that NbTi and Nb_3Sn have a T_C = 9.5K and 18K respectively, but now the critical flux density is in the order of B_C ~ 13T and ~ 23T. This opened up the possibility for superconducting high field magnets. There was however a problem still remaining and that was a limited current density of the superconductor. The resistive state of the metal alloy would rapidly reappear, if the current density J exceeds the critical current density J_C. Many superconducting compounds have been discovered since NbTi where Fig. 1 shows the operation boundaries of temperature and magnetic field for industrial conductors, which will cause the critical current density to vanish. A superconductor cannot support a loss free current if operated above the irreversibility line B_{irr} as shown in Fig. 1. The critical temperatures T_C of the superconductors are marked on the top axis along with the boiling point at atmospheric pressure of several cryogenic fluids – liquid helium (LHe) with 4.2K, liquid hydrogen (LH_2) with 20K, liquid neon (LNe) with 27K, liquid nitrogen (LN_2) with 77K and liquid oxygen (LO_2) with 90K. The top bar indicates the efficiency of typical cryogenic cooling systems [12]. Thus 100W of cooling power at 30K will need 10kW of input power.

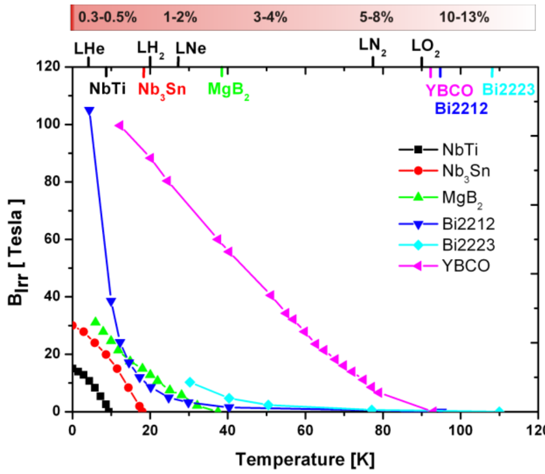

Fig. 1 – Operation boundaries of different superconductors, where the critical current vanishes. The top bar indicated the typical efficiency of a cryogenic cooling system. Reproduced from [11] and [12].

A new class of ceramic superconductors were discovered in 1986 and they were termed high temperature superconductors (HTS), because the critical temperatures T_C = 39-110K were much higher than what could be explained by the theory of superconductivity in metals. Superconductivity in metals is caused by pairing of electrons via a distortion of the crystal lattice, but there is still no final theory of how the pairing is happening in the ceramic superconductors. They have quite complicated chemical composition: $YBa_2Cu_3O_{6+x}$ (YBCO) with T_C = 93K, $Bi_2Sr_2CaCu_2O_{8+x}$ (Bi-2212) with T_C =95K and $Bi_2Sr_2Ca_2Cu_3O_{10+x}$ (Bi-2223) with T_C = 110K. The advantage of the HTS conductors in application is a higher operation field and temperature.

The voltage drop E across a practical superconducting wire is given by a power law relation depending on the current density J compared to the critical current density J_C(T,B), which is a function of temperature and internal magnetic field (2):

$$E = E_0 \left(\frac{J}{J_C(T,B)}\right)^{n(T,B)} \qquad (2)$$

The pre-factor is arbitrarily chosen as E_0 = 1μV/cm as the voltage drop at the critical current density, whereas the exponent n(T,B) quantifies how abruptly the superconductor transitions from non-resistive to resistive state if J_C is exceeded.

2.2 Wires and tapes for applications

The first practical superconducting wires consisted of filaments of the NbTi or Nb_3Sn alloy embedded in a matrix of copper giving a round wire with a diameter of the order 1mm. They were introduced around 1960 and still remain the working horse of the Magneto Resonant Imaging (MRI) industry, NMR spectrometers, accelerator magnets and fusion experiments.

Bi-2223 was the first HTS commercialized in the form of a flat tape (4mm x 0.3mm) and is often called the first generation (1G). It consists of ceramic filaments embedded into a silver matrix needed to allow oxygen to diffuse into the superconductor during processing. The silver is however costly and places a lower limit to how cheap the conductor can become.

A YBCO based conductor was developed as the second generation (2G) technology with the potential of lower material cost. The challenge with YBCO is that wires cannot be produced by powder technologies, but one will have to grow a continuous and aligned thin film of thickness 1-2μm on top of a metal substrate. 2G tapes are still being developed and the production price is still contributing to a large fraction of the wire cost.

Finally it should be mentioned that the MgB_2 superconductor was first discovered in 2001 and has a T_C = 39K. It can be produced by powder methods and is showing critical current densities which are comparable to NbTi, but at a higher temperature. Thus it is an interesting alternative for applications in the T = 10-20K operation range.

The losses in a superconducting wire of length L with a DC current I is given as P = LEI, where the electric field (E) is given by (2). This is however largely increased, if a superconductor is carrying an AC current or is exposed to an AC field, because flux lines will be moved in and out of the superconducting filaments. Small filaments are needed to transfer the heat to the metal matrix. This has been achieved successfully with the low temperature superconductor wires of NbTi and Nb_3Sn, which can contain filaments sizes down to a few micrometers. Such small filament sizes have still not been achieved with the MgB_2 and Bi-2223 conductors and will be very difficult for the YBCO tapes.

The price and performance of the superconducting wires have a large influence on the feasibility of large scale applications of superconductivity. Up till now it is only applications with special demands of high fields (accelerator magnets) or high field and time stability (MRI and NMR magnets), which have been commercialized. More general power applications such as cables, transformers and electrical machines are challenged by the dominating presence of available non-superconducting alternatives. This might not be the case for very large wind turbine generators (+10MW), where current non-superconducting technology might be insufficient due to cost and weight constrains.

Table 1 is showing an estimate of the price per length of the different superconductors in Fig. 1 and it is clearly seen that the high temperature superconductors currently are 1-2 orders of magnitude more expensive than NbTi and Nb_3Sn. An estimate of the engineering current density J_e defined as the critical current divided by the cross section of the wire is also listed. From a practical point of view a J_e in the order of more than 100 A/mm^2 is desirable and is first obtained well below the T_C and B_{Irr} of fig 1. The LTS are restricted to operation temperatures around T = 5-10K giving a high J_e, but the cooling efficiency is in the order of 0.3% (see fig. 1). At T = 20K the cooling efficiency becomes 1% and the J_e of the MgB_2 conductor starts to be comparable to the HTS, but at a lower price. However if the cooling efficiency is increased to 3-4% by increasing the operation temperature to T = 50K it is seen that only the YBCO superconductor will provide reasonable current densities, because the B_{Irr} of Bi-2223 collapses far below T_C on fig 1.

Type	Price €/m	J_e A/mm^2	Flux density [T]	Temp. [K]
NbTi	0.4	10^3	5	4.2 [13]
Nb_3Sn	3	$1\text{-}4x10^3$	5	4.2 [14, 15]
MgB_2	4	10^2	3	20 [11, 14, 16]
Bi-2223	20	390 10	3 ⊥tape 3 ⊥tape	20 [17] 50
YBCO	30	98 (480) 49 (190)	3 ⊥tape 3 ⊥tape	20 [18] 50

Table 1 – Price of superconductors and the engineering current density at typical operating conditions of flux density and temperature. ⊥tape indicates that the flux density is perpendicular to the tape. The values shown in () refer to 2G tapes with thin substrate produced by SuperPower.

From a machine design point of view it is important to know what engineering current density (J_e) (defined as current in the wires divided by the wire cross sectional area), one can obtain in the field windings. Table 1 illustrates that the low temperature superconductors have very high J_e at liquid helium temperature. It is also clear that MgB_2 has very high potential, if operating temperatures of 15-20K can be reliably achieved.

The cryogenic challenges of operating at 4.2K are significant and the possible higher operation temperature of the HTS is attractive, because the cooling can be provided by cryocooler machines. Thus the optimal choice of superconductor for future large wind turbine generator is still an open question and will be determined by improvements in the production price and higher engineering current densities. The choice of superconductors for possible future wind turbine generators will therefore be a trade-off between wire cost, and cooling cost and complexity, where the winning solution is the one that provides the lowest CoE.

3 Superconducting machines

The importance of higher efficiency, improved stability and outstanding power density of electrical machines was well known when the first superconducting machines were demonstrated in the early 1960's [19].

The idea to improve the conventional design of electric machines has been tried in the past with Low Temperature Superconductors (LTS) in several demonstration projects [19], many of which were successful and proved the merits and technical feasibility of superconducting machines. However, operational temperatures between of 2K - 4K of LTS and the complexity and cost of the refrigeration system impeded commercialization of LTS machines.

With the discovery of HTS materials, superconducting machines have again become interesting from a commercial point of view. The difference between LTS and HTS is not only in temperature range, which for HTS is substantially higher and can be between 30K and 80K, but also a device employing HTS can operate in a much wider temperature window This has profound effects on the refrigeration complexity and efficiency as shown by the top bar of fig. 1. The refrigeration system and thermal insulation in an HTS application can therefore be simpler and more efficient compared to LTS and MgB_2 systems.

3.1 Power and torque density

To understand the motivation for superconducting machines, first it is important to understand the limitations of conventional machines. The power of any rotating device is the torque times the rotational speed (3). The electromagnetic torque of an electrical machine is proportional to the armature electric loading (*A*), the peak airgap flux density (*B*) and the volume enclosed by the airgap (*V*), as expressed in (4).

$$P = \mathrm{T} \times \omega \tag{3}$$

$$T \propto B \times A \times V \tag{4}$$

For conventional electrical machines, the product *B x A* is limited by material properties. Maximum values of peak airgap flux densities (*B*) in conventional designs are limited to 1T due to saturation of the laminations. On the other hand, the electric loading (*A*) is limited by dissipated heat and maximum temperature of the electric insulation to values less than 150 kA/m with forced air cooling [20].

Thus, with *B x A* limited, a closer look at the torque expression reveals that the torque (*T*) in a conventional machine is directly proportional to the size of the machine (*V*).

Using a superconducting electromagnet, with practically lossless magneto-motive force (MMF), the product *B x A* could be doubled or tripled by increasing the peak airgap flux density to 2-3T. Accordingly, superconducting machines can be made significantly smaller than conventional machines.

3.2 Direct drive wind turbine generator

As mentioned earlier, many of the wind turbine manufacturers have started manufacturing large direct drive wind turbines. This trend will only continue if the size and weight of the direct drive generators is limited such that the CoE can continue to decrease. There is therefore a large incentive for economical torque dense generators for future wind turbines.

3.3 Types of Superconducting machines

Superconducting technology has been proposed for several machine types [21, 22, 23, 24, 25, 26, 27, 28, 29] however, most high power demonstrations of superconducting machines have been synchronous machines with superconducting field windings.

Two concepts of superconducting machines have been proposed. In the first, only the field winding is superconducting, whereas in the second both armature windings and field windings are superconducting, normally referred to as fully superconducting machines. Fig. 3 shows the axial-radial cross section of a superconducting synchronous machine, where the field winding is superconducting and the armature winding is copper. The superconductor is thermally insulated from ambient and the cold section is equipped with a torque transfer element, which both insulates and transfers the torque from the cold region to the warm region.

Intuitively the logical place to employ superconductors is in the field winding of a synchronous machine, as it is powered with DC current and is exposed to DC flux. The armature windings carry AC currents and are exposed to AC flux. This can result in large AC losses if superconductors are employed in the armature.

However, superconductors are improving continuously and are becoming more and more suitable for AC applications. Thus, with fully superconducting machines the *B x A* product can be pushed even further by boosting both the airgap flux density and the electric loading.

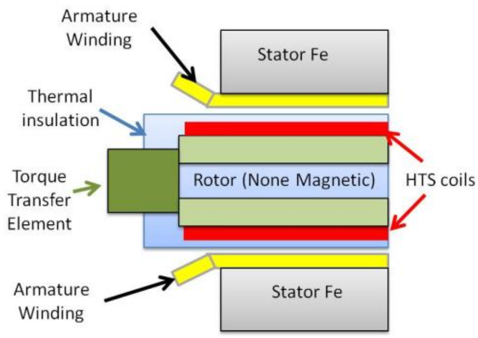

Fig. 3 – Axial-radial cross section of a superconducting synchronous machine

3.4 HTS machine demonstrators

A numbers of projects have successfully shown the technical feasibility of large HTS machines. These have all been based on 1G tape, but there are several plans of constructing large demonstrators with 2G tape.

In Europe, Converteam constructed a 1.79 MW, 28 pole, 214rpm hydroelectric generator [30], which was a retrofit of an older hydroelectric generator. The HYDROGENIE HTS generator with a rated torque of 80.3kNm has 1G HTS field windings, which are cooled to 30K using high pressure helium gas [31]. The helium gas is transferred from static cryocoolers (GM) to the rotor via a bespoke rotating coupling [32]. The rotor steel in the machine is kept at room temperature and the stator has conventional slots [31].

Two HTS synchronous machine prototypes have been reported by Siemens with cold rotor steel [33]. The first machine was 400kW, 1500rpm with HTS field windings made from 1G BSCCO coils, with a slotless armature winding [34]. The machine was operated at 25K, cooled by a GM cryocooler placed outside the machine, where liquid neon served as the cooling medium [35]. The second machine had a rating of 4MW with an identical design concept also employing 1G HTS in the field winding [10, 36]. Both motors were developed for ship propulsion as the primary application field [10].

Several machines were constructed in projects led by American Superconductor (AMSC). AMSC designed, built, and tested a 3.5MW four pole, 1800rpm machine [8]. In this design, the whole rotor, including coils wound with BSCCO HTS conductor, was cooled down to 35K using a closed cycle neon heat pipe concept [37]. Under contract with the Office of Naval Research, AMSC built two prototype motors: a 5MW and 230rpm motor [38], and a 36.5MW and 120rpm motor [39]. The motors were constructed as power compact ship propulsion alternatives to existing ship propulsion concepts [38]. The armature on these motors was liquid cooled with dielectric insulating oil. Both motors employed 1G (BSCCO) field windings cooled with GM cryocoolers and operated at 30K.

The 36.5MW machine developed by AMSC presents the highest torque HTS machine publicly reported up to date with an output shaft speed of 120rpm, and over 2.9MNm of torque at a weight estimate of 75 tons [9].

Several plans have been put forward to design and construct 8-10 MW wind turbine generators. Converteam came with an air core HTS machine using 1G HTS tape [40]. AMSC have also announced intentions to construct a direct drive wind turbine generator under the brand name SeaTitan [41], see Fig. 4.

GE recently started a project with funding from the US DOE to investigate a 10MW-15MW [42] direct drive wind turbine where the primary investigation will also include LTS technology, see Fig. 5.

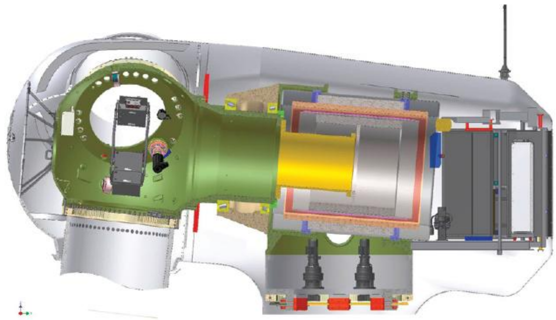

Fig. 4 – 10MW SeaTitan offered by AMSC. Reproduced with permission from AMSC.

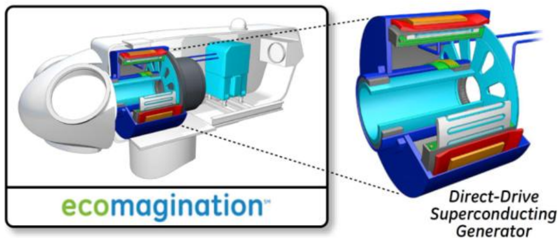

Fig. 5 – Direct drive superconducting wind turbine generator from GE. Reproduced with permission from GE.

3.5 Fully superconducting machines

There have been several suggestions for large utility fully superconducting generators using LTS [43, 44] and a very limited number of laboratory-scale projects of fully superconducting machines using HTS conductors [45]. The obvious advantage of fully superconducting machine is that both the airgap flux density and the electric loading can be increased beyond that of conventional machines [46].

Additionally, if both armature and field windings operate at the same temperature, the airgap can be made much smaller, as no thermal insulation is required between the two, and thus the whole magnetic design of the machine becomes more efficient. Nevertheless, the largest issue in this concept is AC losses generated in the armature winding. At the moment, the amount of ac loss in high field AC application is regarded as prohibitive [9] due to poor cooling efficiency.

However, a proposal for a 10MW fully superconducting wind turbine generator has been put forth by AML employing a rotor with Double-Helix configuration and MgB_2 superconductors on both rotor and stator [47]. An illustration of this generator in a nacelle is seen in Fig. 6.

3.6 Challenges

Superconducting machines may have the potential of increasing the torque density by a factor of 2-3 compared to conventional machines. However, this is not without challenges. The size of the machine may be reduced by increasing the airgap flux density, but the weight of the machine will not decrease proportionally with the size. The reason for this is that the higher airgap flux density will require more structural support than a similar size conventional machine.

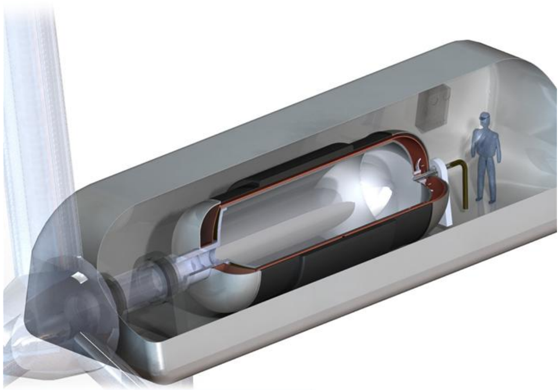

Fig. 6 – 10MW fully superconducting wind turbine generator proposed by AML [47]. Reproduced with permission from AML.

The high magnetic flux from the superconducting electromagnet needs to be shielded from the ambient for safety reasons, and such that eddy currents are not induced in any conductive components in the vicinity. The superconducting machine therefore required a soft magnetic coreback as is known from conventional machines.

An effective way of reducing the weight of a direct drive permanent magnet wind turbine generator is by employing multiple poles. As the number of poles is increased the coreback thickness can be reduced because it carries less magnetic flux. This is however not as easily achieved in a superconducting machine where the mmf is supplied by a superconducting electromagnet. If the number of poles in a superconducting machine is increased, the amount of superconducting wire is also increased and hence the price of the machine is increased [18]. This price increase can be very significant because the superconducting wire is currently very expensive.

The reliability of a superconducting wind turbine generator is still not known and could pose a significant challenge. The cryogenic cooling system is an added complication which is not found in conventional wind turbine generators. Additionally the effective airgap in a superconducting machine is relatively large resulting in a low synchronous reactance and hence large fault currents and torques. These large fault currents and torques are design challenges, the effect of which can be tested experimentally on a prototype in a controlled environment. The reliability is also is a design challenge; however it can only be validated from extensive operational experience and hence is a challenge that will persist for a number of years.

Currently the production capacity of HTS and MgB_2 is not adequate for large scale commercialization of superconducting wind turbine generators. As LTS is used extensively in commercial and research applications e.g. MRI scanners and accelerator magnets, the production capacity of LTS is significant. However, this would have to increase further if another large application area opened up.

The challenges of superconducting wind turbine generators are therefore substantial and of a wide nature, spanning machine design and construction; system reliability; and production capacity of the superconducting wire.

4 Commercial indicators

Superconducting high torque machines could become commercially attractive, provided that the cost and production capacity of the superconductors are improved. There are several companies that have been involved in the development of superconducting technology. This can be seen from the patent development in the field of superconducting machines dating from 1965.

The first patents in the field of superconducting machines focused on the use of LTS in field windings of large turbo generator. More recently, with the discovery of HTS and MgB_2, the patents have opened up for any kind of superconductors and have focused on electrical machines as well as other applications.

A simple search in the Web of Knowledge – Derwent Innovations Index^{SM}, using a combination of the terms “Supercond*” and “machin*“, where ‘*’ allows any possible combination of non-specified characters with the specified string, yields 871 hits in total from 1965 up to date. By breaking down this number of inventions into patents in each decade and assignees, Fig. 7 shows a sharp increase from 89 to approximately 300 inventions per decade after 1980.

The high number of inventions associated with

Asian companies in the first three decades stems from the efforts invested into large LTS turbogenerators. However, with LTS machines ramping down in the last two decades, HTS machines have stepped in and in total claimed almost identical amount of inventions. Companies like Siemens, General Electric and American Superconductor stand out when it comes to HTS machine inventions, where medium torque ship propulsion high efficiency motors have been a focus of Siemens and American Superconductor for a larger part of the last decade. Lately, also very high torque HTS machines have drawn attention.

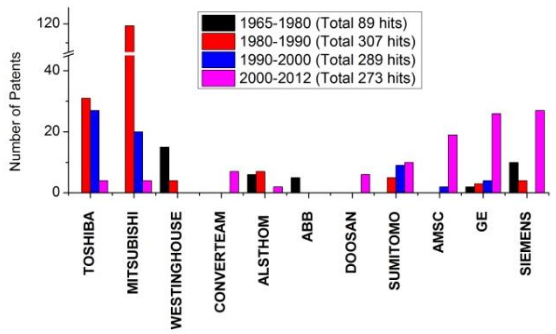

Fig. 7 – Results of the search from one of the patent database presenting the innovation intensity relating to superconducting machines.

High torque superconducting generators for wind turbines offer very interesting business opportunities, as alternative conventional generators when reaching 10MW and beyond are scarce. Since 2005 companies and research institutions have claimed inventions relating to superconducting machines in wind turbines.

GE had three patents (covering US, China and EU) in 2008, 2009 and 2011. Alstom had two patents in 2006 where one is shared with Converteam and AMSC has a patent from 2011. From this observation it would look like the companies are preparing for the technology leap that might be necessary for large-scale (+10MW) offshore turbines.

It should be kept in mind that a large number of inventions useful for HTS machine design are likely to be overlooked in this search, due to either the complex formulation of the patents or different classification, e.g. technical solutions from superconducting magnet technology could successfully be used in design of HTS machine.

5 Discussion

There are a large number of challenges associated with employing superconductors in wind turbine generators. These challenges are easier met in collaboration between wind turbine manufacturers, wind farm developers/operators, and superconducting wire manufacturers.

The wire manufacturers are unlikely to invest in expanding their production capacity unless they see a demand or a commitment from an end-user; here their end-users are the wind turbine manufacturers. The wind turbine manufacturers are unlikely to start manufacturing superconducting wind turbine generators unless they have access to sufficient supply of superconducting wire and see a demand or a commitment from their end-users, which in this case are the wind farm developers/operators. A commitment from all three parties would therefore be needed for large-scale rollout of superconducting wind turbine generators.

Analyzing the patent development in the field of superconducting machines from 1965 till now, it is clear that some of the largest manufacturing companies have remained active in this field for decades, and have intensified their intellectual property protection over the last decade.

Although all three mentioned superconductors: LTS, HTS and MgB_2, have their advantages and challenges, it is interesting to see that the industry is divided and all three alternatives are being proposed for large direct drive wind turbines.

6 Conclusion

One can thus conclude that superconducting machines have retained industrial interest for decades, though no commercialization has occurred yet. Additionally the future of superconducting machines is unknown, but they might be a feasible alternative for very large +10MW offshore wind turbines. It is however unclear whether the future generators will converge towards only one superconducting technology or whether all three alternatives: LTS, HTS and MgB_2 will be seen in the future.

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